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MECHANICAL PROPERTY CHARACTERIZATION OF VASCOMAX T-300

CHARLES F. HICKEY, Jr., DAVID W. DIX, and DAVID KAGAN
MATERIALS PRODUCIBILITY BRANCH

August 1989

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ABSTRACT

This report addresses a mechanical property characterization of 18% Ni 300 grade cobalt-free maraging steel (T-300). Hardness, tensile, Charpy V-notch impact energy, and fracture toughness data were obtained for a 2-3/8-inch-diameter forged bar. These data are presented along with existing data on stress corrosion, microstructure, and ballistic performance for this and other maraging steels.

The results indicated that the mechanical properties are more dependent on the aging temperature than on the aging time for the temperatures of 900°F and 950°F, and times of 3 and 4 hours. Both hardness and Charpy impact energy were unaffected by varying the aging temperatures and times, while the tensile properties and fracture toughness increased in response to the increase in aging temperature. Based on the information obtained in this study and the existing information available on this alloy, the recommended aging treatment is 950°F for 4 hours.

BACKGROUND AND INTRODUCTION

The cobalt-containing 18% Ni maraging steels were developed by the International Nickel Company (INCO) during the early 1960's.[1] Four tensile strength levels (grades) were developed, namely 200, 250, 300, and 350 ksi, with each grade differing principally in its level of titanium and cobalt. These steels, especially the 250 and 300 grades, have received rather wide use in production tooling, aerospace, and military applications. Relative to the latter, the 300 grade has been used extensively as a missile motor case material in the TOW and Stinger systems. This grade contains between 8.5 to 9.5 wt% cobalt.

In the late 1970's, cobalt became a critical and strategic element to the United States, creating the need to minimize our foreign dependency by way of alloy modification. In 1980, INCO developed cobalt-free versions of the 18% Ni maraging steels. The initial alloys had relatively poor toughness properties but INCO felt that better compositions could be defined. They then entered into a program with Teledyne Vasco and the alloys designated as VascoMax T-250 and T-300 were developed. The basic difference between these alloys and the existing grades of maraging steel is that these are cobalt-free and contain more titanium and less molybdenum than the corresponding cobalt-containing grades. Teledyne Vasco is now producing both of these alloys in full-scale production heats, with T-300 being the material addressed in this report.

The properties investigated in this report are hardness, tensile, Charpy V-notch impact energy, and fracture toughness with reference to data on stress corrosion cracking, microstructure, and ballistic performance. The aging conditions used in this study, 900°F and 950°F for 3 and 4 hours, evolved from the investigation of the 250 grade maraging steel (T-250).[2] In T-250, aging temperatures greater than 1000°F and prolonged aging times resulted in an overaged condition with the formation of reverted austenite.* At present, the authors have not investigated T-300 at these elevated temperatures and times.

MATERIALS AND PROCEDURES

The 2-3/8-inch-diameter forged bar, supplied by Teledyne Vasco, was induction vacuum melted (IVM) into a 17-inch-diameter electrode and then consumable vacuum melted (CMV) into a 20-inch-diameter ingot. The ingot was homogenized and forged into 6-inch-diameter billets then forged into 2-3/8-inch-diameter bars. The bars from heat number 6892A, having the chemical composition outlined in Table 1, were double annealed at 1700°F and 1500°F. The 3/4-inch plates used for the stress corrosion studies were induction vacuum melted and then consumable vacuum melted prior to rolling. The plates from heat number 7781A, having the chemical composition shown in Table 1, were annealed at 1500°F.

*Hickey, C. F., Jr. Cobalt-Free Maraging Steels. To be published.

1. Source Book on Maraging Steels. Raymond F. Decker, ed., ASM, Metals Park, Ohio, 1979.
2. HICKEY, C. F., Jr., and THOMAS, T. S. *Mechanical Characterization of VascoMax T-250.* U.S. Army Materials Technology Laboratory, MTL TR 86-30, July 1986.

Table 1. CHEMICAL ANALYSIS OF T-300, (WT%); BALANCE Fe

Heat No.	C	Mn	P	S	Si	Ni	Co	Mo	Ti	Al	Cu	W	Cr
7781A	0.005	0.02	0.009	0.005	0.03	19.00	0.55	4.03	1.90	0.13	0.09	0.02	0.22
6892A	0.005	0.02	0.009	0.002	0.01	18.42	0.34	4.08	1.86	0.10	–	–	–

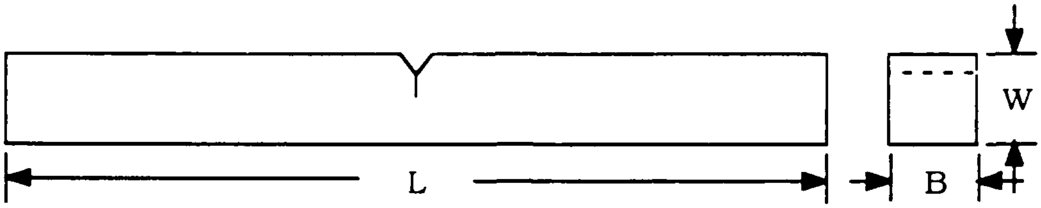
All specimens were rough machined into the "blanked" form prior to heat treating. Those from the 2-3/8-inch-diameter bar that were used for hardness, tensile, Charpy impact, and fracture toughness tests were solution annealed at 1500°F for 1 hour and air cooled prior to aging. The plates used for the stress corrosion study were annealed at 1500°F and aged at 900°F for 3 hours.

The tensile and fracture toughness specimens were machined in the longitudinal direction only, while the Charpy V-notch impact specimens were machined in both the longitudinal and radial directions. The longitudinal orientation (L-R) indicates a specimen whose length is parallel to the axis of the rod with the crack propagating in the radial direction, and the radial orientation (R-L) indicates a specimen whose length is perpendicular to the axis of the rod with the crack propagating in the axial direction. Buttonhead type specimens, 0.252 inch diameter, were used in the tensile tests, standard V-notch Charpy impact specimens (type CV-2) and precracked Charpy specimens were used to generate impact energy data and fracture toughness data, respectfully. The fracture toughness data is expressed as K_{IQ} which is a conditional plane-strain (K_{IC}) value.

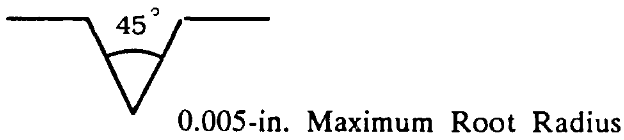
Stress corrosion data on T-300 was obtained in plate form by J. Scanlon of MTL in conjunction with data on VascoMax T-250, C-300, and C-250.[3] The machining of the specimens was completed, as dimensioned in Figure 1, in the L-T orientation, i.e., the length of the specimen was in the longitudinal (rolling) direction with the crack propagating in the transverse direction. After finish machining, all specimens were fatigue precracked such that the aspect ratio, a/W (ratio of notch plus precrack to total specimen depth), was in accordance with ASTM E 399 for cantilever beam specimens.[3,4]

The specimens were secured horizontally into the test apparatus described by Brown,[5] and as shown in Figure 2. A polyethylene cell, containing approximately 50 ml of neutral 3.5 wt% NaCl solution, was placed surrounding the notched area. The tests were run under freely corroding conditions and the solution was changed daily except on weekends. The crack length that was used to calculate K_{IC}, outlined in Figure 1, was measured at three interior points of each specimen and averaged. The threshold intensity level, K_{Iscc}, was estimated as the value between the stress intensities which did and did not cause failure in the 1000-hour test duration.[3]

3. HICKEY, C. F., Jr., et al. *MTL Evaluation of TOW Missile Motor Case Failures and Stress Corrosion of Maraging Steels.* MTL Letter Report, August 1988.
4. Standard Method of Test for Plane Strain Fracture Toughness of Metallic Materials. Annual Book of ASTM Standards, ASTM Standard E 399, 1974.
5. BROWN, B. F. *A New Stress Corrosion Cracking Test for High-Strength Alloys.* Materials Research and Standards, v. 6, no. 3, March 1966, p. 129-133.



L = 6.0 in.
W = 0.5 in.
B = 0.5 in.



$$K = \frac{4.12\,(\alpha^{-3}-\alpha^{3})^{1/2}\,M}{BW^{3/2}}$$

where: $\alpha = 1 - a/W$
a = crack length + notch depth

Figure 1. Stress corrosion specimen.

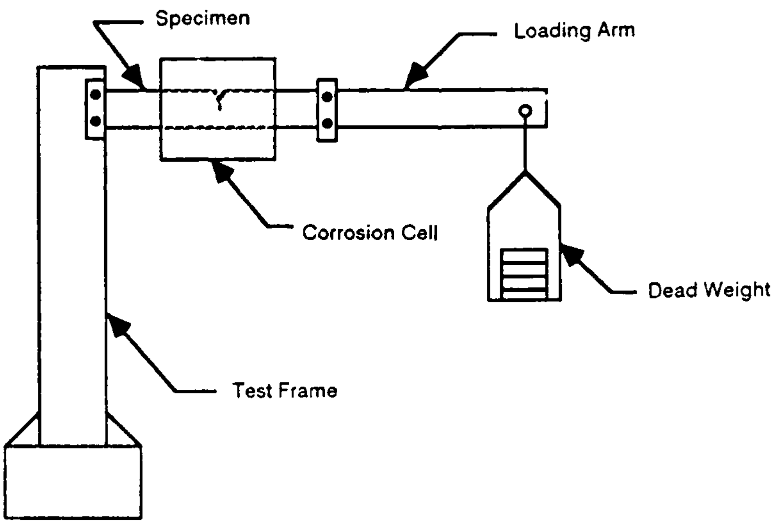


Figure 2. Schematic of stress corrosion test apparatus.

RESULTS AND DISCUSSION

Hardness

Rockwell C hardness readings (HRC) are tabulated in Table 2 as a function of aging time and temperature. Hardness was independent of aging temperature and time; values between 53.8 and 54.4 were obtained. Each hardness value is an average of four readings from each of two Charpy impact specimens.

Table 2. EFFECT OF AGING TREATMENT ON HARDNESS (HRC)

Aging Temp. (°F)	3-Hour Age	4-Hour Age
900	53.8	54.4
950	53.9	54.2

Tensile Properties

The yield strength, ultimate tensile strength, percent elongation, and reduction of area are tabulated in Table 3. Increases in the 0.2% yield strength to 280 ksi and the ultimate strength to 293 ksi were obtained by raising the aging temperature from 900°F to 950°F. The ductility remained relatively constant at 10.5% to 11.0% elongation and 49.0% to 52.2% reduction of area for the investigated aging treatments.

Table 3. EFFECT OF AGING TREATMENT ON TENSILE PROPERTIES

		3-Hour Age				4-Hour Age			
Aging Temp. (°F)		0.2% YS (ksi)	UTS (ksi)	Elon. (%)	RA (%)	0.2% YS (ksi)	UTS (ksi)	Elon. (%)	RA (%)
900		269	285	10.2	49.2	267	283	10.2	48.6
		261	279	11.3	49.2	269	287	10.8	49.4
	(Avg.)	265	282	10.8	49.2	268	285	10.5	49.0
950		281	291	11.2	52.0	285	295	10.5	51.4
		277	291	10.0	52.3	275	290	11.5	50.3
	(Avg.)	279	291	10.6	52.2	280	293	11.0	50.9

Fracture Toughness

The fracture toughness (K_{IQ}), shown in Table 4, was found to exhibit a greater dependence on the aging temperature than the aging time. The values obtained from the specimens aged at 950°F gave values ranging from 63.0 to 68.2 ksi$\sqrt{\text{in.}}$, whereas the values obtained from the 900°F aging temperature ranged from 71.8 to 74.4 ksi$\sqrt{\text{in.}}$

Tensile Strength Versus Fracture Toughness

Figures 3 and 4 are plots of tensile strength versus fracture toughness as functions of aging time and temperature for T-250 and T-300. The attainment of maximum values for tensile strength and fracture toughness at the 950°F aging temperature is consistent in both of these alloys.

Table 4. EFFECT OF HEAT TREATMENT ON FRACTURE TOUGHNESS, K_{IQ} (ksi$\sqrt{in.}$)

Aging Temp. (°F)		3-Hour Age	4-Hour Age
900		66.9	67.8
		*	63.0
		68.2	66.6
	(Avg.)	67.6	65.8
950		73.1	74.4
		72.3	74.1
		71.8	73.8
	(Avg.)	72.4	73.8

*Recorder malfunction

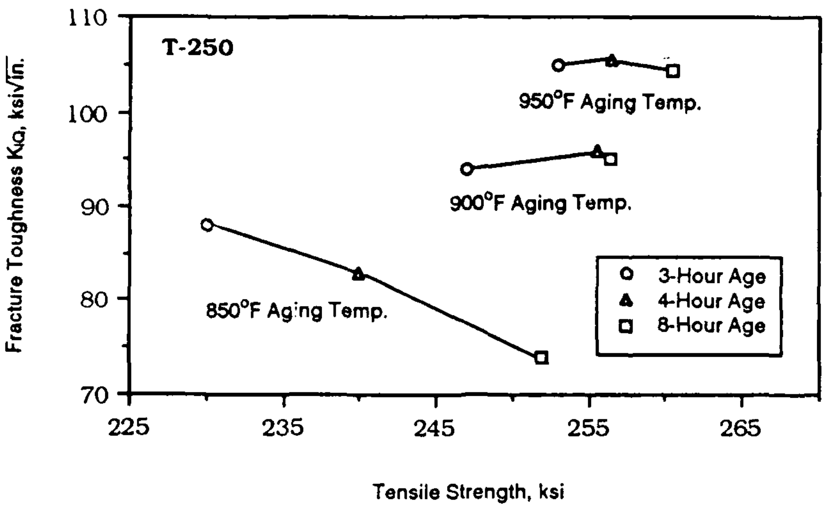


Figure 3. Fracture toughness versus tensile strength for T-250 (Ref. 2).

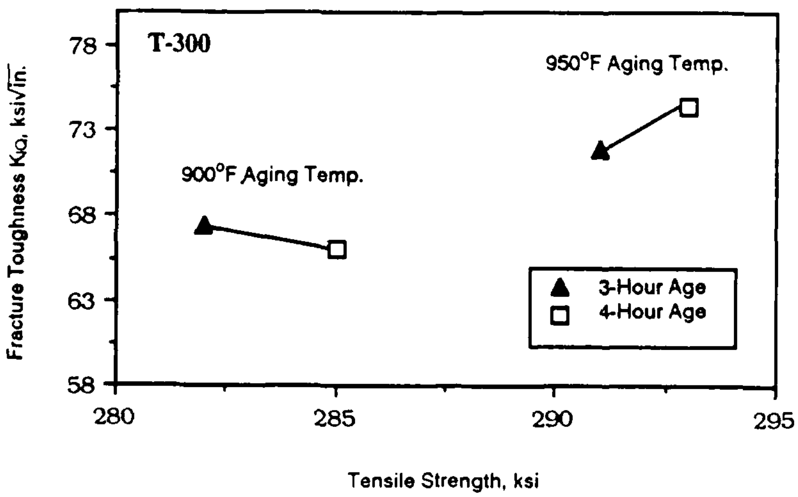


Figure 4. Fracture toughness versus tensile strength for T-300 (Ref. 2).

Charpy Impact Energy

Charpy impact energy data, as a function of heat treatment and specimen orientation, is tabulated in Table 5. As would be expected, the values in the longitudinal direction (L-R orientation) are significantly greater than those in the transverse direction (R-L orientation), yet there was little variation in the results between aging treatments in similarly oriented specimens. The values obtained in the longitudinal direction gave values from 14.0 to 14.5 ft-lb, whereas the values obtained from the transverse direction ranged from 10.4 to 11.8 ft-lb.

Table 5. EFFECT OF AGING TREATMENT AND ORIENTATION ON CHARPY IMPACT ENERGY

Orientation	Aging Temp. (°F)		3-Hour Age (ft-lb)	4-Hour Age (ft-lb)
Longitudinal	900		13.1	14.1
			14.9	14.0
		(Avg.)	14.0	14.1
Longitudinal	950		14.1	14.8
			14.8	13.9
		(Avg.)	14.5	14.4
Transverse	900		10.5	10.9
			10.3	12.7
		(Avg.)	10.4	11.8
Transverse	950		10.5	10.4
			12.9	10.6
		(Avg.)	11.7	10.5

Stress Corrosion Resistance

Tabulated in Table 6, for T-300, C-300, T-250, and C-250, are K_{Iscc} values of 16, 18, 21, and 29 ksi$\sqrt{\text{in.}}$, respectively.[3] The designation for these alloys is such that the prefixes T and C represent cobalt free and cobalt containing, respectively, and the suffix represents the approximate tensile strength in ksi. Figure 5 shows a plot of initial stress intensity versus time-to-failure for T-300, initially supplied in plate form. The K_{Iscc} value is estimated from the graph and is accurate to ±3 ksi$\sqrt{\text{in.}}$ for this material. Through fractographic analysis, the fracture surface of T-300 revealed a quasi-cleavage appearance with areas of transgranular attack, dimpling, and limited regions of intergranular corrosion.[3] It is worth noting that of the alloys examined, including both the C and T, the alloys of higher strength have a greater susceptibility to stress corrosion cracking than those of lower strength. Overall properties and fracture surface appearance for all of the alloys examined are contained in Table 6.

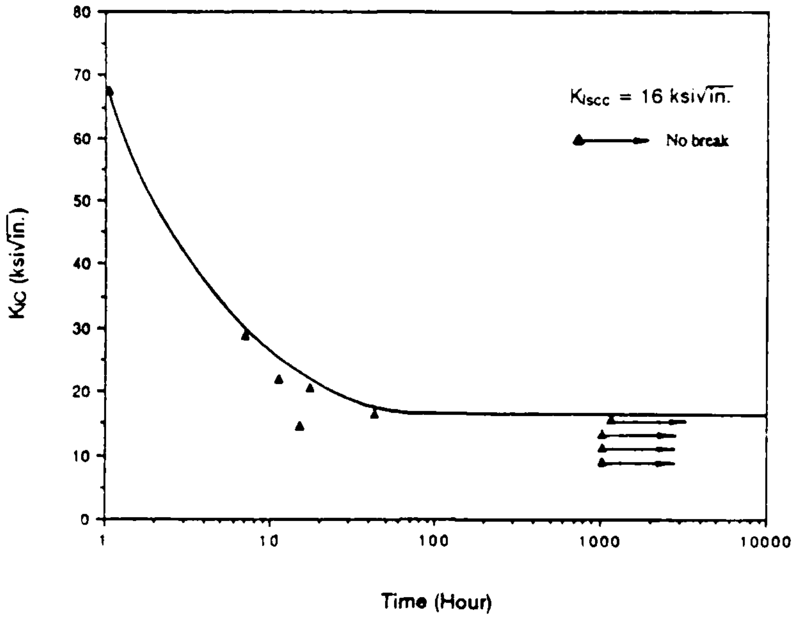


Figure 5. Stress intensity versus time-to-failure for T-300 (Ref. 3).

Table 6. SUMMARY FOR SCC OF MARAGING STEELS (REF. 3)

Alloy	0.2% YS (ksi)	K_{IQ} (ksi√in.)	K_{Iscc} (ksi√in.)	Fracture Surface
C-250	250	110	29	Quasi-Cleavage
C-300	270	70	18	Intergranular
T-250	249	95	21	Quasi-Cleavage
T-300	265	68	16	Intergranular

Microstructure

Microstructures of the four aged conditions in the 2-3/8-inch-diameter bars were examined. All specimens from the bars exhibited an average grain size of 8. Typical microstructures for each of the aging conditions studied are shown in Figures 6 through 9. Each of these were polished and etched in a solution of $FeCl_3$ and HCl in ethanol, and then washed with an ammonia/hydrogen peroxide solution to increase visibility. Aged low carbon martensite was observed in the 900°F and 950°F aged conditions for both the 3- and 4-hour aging times.

Vanderwalker, at MTL, determined in a TEM study that the shape and orientation of Ni_3Ti precipitates in T-250 were determined by the size of austenite crystals.[6] In a subsequent TEM study, the condition of the Ni_3Ti precipitates in T-300 and C-300 were observed to be rods in lath martensite for both alloys. The microstructure of T-300 also showed evidence of large multiphase particles consisting of Fe_2Mo, FeMo, and possibly Fe_xTi. These particles are not present in C-300, thus the increase level of cobalt is believed to increase the solubility of Mo. These large multiphase particles, especially Fe_2Mo, have different properties than the martensite causing "soft spots"

6. VANDERWALKER, D. N. *The Precipitation Sequence of Ni_3Ti in Co-Free Maraging Steel.* The Metallurgy Transactions, v. 18A, 1987, p. 1191.

which could be responsible for lower fracture toughness values experienced in T-300 when compared to C-300 and T-250.[7]

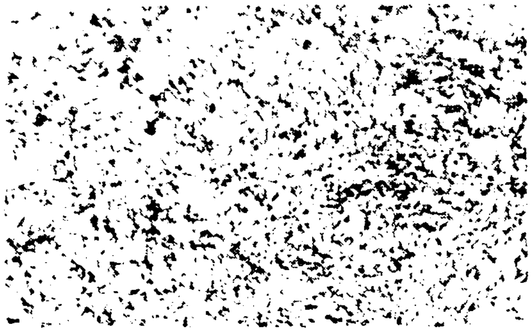


Figure 6. Aged 900°F/3 hours, Mag. 500X.

Figure 7. Aged 900°F/4 hours, Mag. 500X

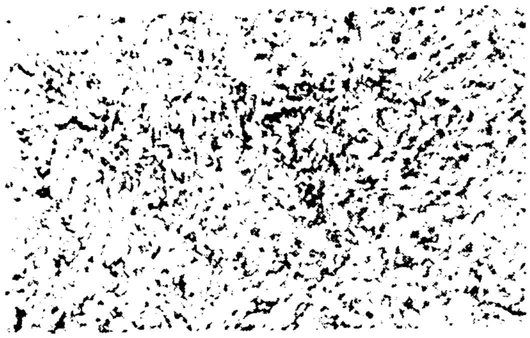


Figure 8. Aged 950°F/3 hours, Mag. 500X.

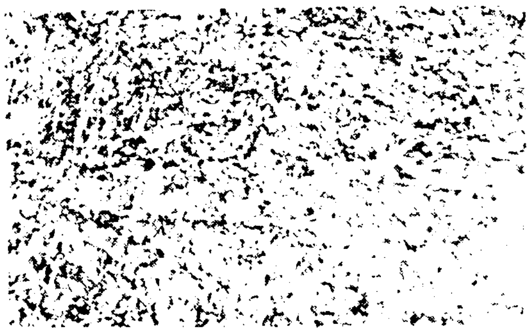


Figure 9. Aged 950°F/4 hours, Mag. 500X.

Ballistic Performance

Ballistic evaluations were carried out by Hickey, at MTL, on T-300 and T-250 solutionized at 1500°F for 1 hour, air cooled, and aged for 4 hours at 900°F in an air furnace. In response to both .30 and .50 caliber armor piercing (AP) threats in 0.25-inch and 0.50-inch plates, T-250 performed the best. The .30 caliber 0.25-inch plate tests resulted in good multihit capability and an encouraging protection limit. The same .30 caliber AP threat shattered the 0.25-inch-thick T-300 plate, perhaps due to the higher hardness as a result of increased Ni_3Ti precipitation.[8]

7. VANDERWALKER, D. N. Maraging Steels - Recent Developments and Applications. R. K. Wilson, ed., TMS-AIME, Warrendale, PA, 1988, p. 255-258.
8. HICKEY, C. F., Jr. *Cobalt Free Maraging Steel.* 3rd US-ROK Materials Symposium, Pohang Steel Co., Korea, 3 November 1988.

SUMMARY AND CONCLUSIONS

This investigation was primarily concerned with the characterization of cobalt-free T-300 maragin^ steel. Also of interest are the property comparisons of T-300 with previously compiled data on this and other maraging steel alloys. Contained in this report is data on tensile properties, hardness, Charpy V-notch impact energy, and fracture toughness of T-300, along with previously obtained data on stress corrosion, microstructure, and ballistic performance.

The results indicate that the mechanical properties are more dependent on the aging temperature than on the aging time for the treatments investigated. Both hardness and Charpy impact energy remained relatively unchanged through the range of aging temperatures and times, while tensile properties and fracture toughness increased in response to the increase in aging temperature from 900°F to 950°F. Microstructural analysis indicated that the property increase could have been due to the increased formation of Ni_3Ti precipitates at the higher aging temperature. Ballistic testing on 0.25-inch plates of T-300 and T-250 against .30 caliber AP rounds revealed good multi-hit capability for the T-250, while the T-300 shattered.

In response to stress corrosion tests on T-250, T-300, C-250, and C-300, both of the cobalt-containing alloys exhibited greater resistance to stress corrosion than their cobalt-free counterpart, with T-300 showing the lowest resistance of all of the alloys examined. Fractographic analysis of T-300 revealed a quasi-cleavage appearance with areas of transgranular attack, dimpling, and intergranular corrosion.

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This report addresses a mechanical property characterization of 18% Ni 300 grade cobalt-free maraging steel (T-300). Hardness, tensile, Charpy V-notch impact energy, and fracture toughness data were obtained for a 2-3/8-inch-diameter forged bar. These data are presented along with existing data on stress corrosion, microstructure, and ballistic performance for this and other maraging steels. The results indicated that the mechanical properties are more dependent on the aging temperature than on the aging time for the temperatures of 900°F and 950°F and times of 3 and 4 hours. Both hardness and Charpy impact energy were unaffected by varying the aging temperatures and times, while the tensile properties and fracture toughness increased in response to the increase in aging temperature. Based on the information obtained in this study and the existing information available on this alloy, the recommended aging treatment is 950°F for 4 hours.

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MECHANICAL PROPERTY CHARACTERIZATION
OF VASCOMAX T-300 - Charles F. Hickey, Jr.,
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